



Published in final edited form as:

J Safety Res. 2020 September ; 74: 219–225. doi:10.1016/j.jsr.2020.06.005.

TRACTION PERFORMANCE ACROSS THE LIFE OF SLIP-RESISTANT FOOTWEAR: PRELIMINARY RESULTS FROM A LONGITUDINAL STUDY

Sarah L Hemler^a, Erika M. Pliner^a, Mark S. Redfern^a, Joel M. Haight^b, Kurt E. Beschorner^a

^aDepartment of Bioengineering, University of Pittsburgh, 301 Schenley Place, 4420 Bayard Street, Pittsburgh, PA 15213

^bDepartment of Industrial Engineering, University of Pittsburgh 1025 Benedum Hall, 3700 O'Hara Street, Pittsburgh, PA 15261

Abstract

Introduction—Slips, trips, and falls are a major cause of injury in the workplace. Footwear is an important factor in preventing slips. Furthermore, traction performance (friction and under-shoe fluid drainage) are believed to change throughout the life of footwear. However, a paucity of data is available for how traction performance changes for naturally worn, slip-resistant footwear.

Method—The presented research is a preliminary analysis from an ongoing, larger study. Participants wore slip-resistant footwear while their distance walked was monitored. Friction and under-shoe fluid pressures were measured using a robotic slip tester under a diluted glycerol contaminant condition after each month of wear for the left and right shoes. The size of the worn region was also measured.

Results—Friction initially increased and then steadily decreased as the distance walked and the size of the worn region increased. Fluid pressures increased as the shoes were worn and were associated with increased walking distance and size of the worn region.

Discussion—Consistent with previous research, increases in the size of the worn region are associated with increased under-shoe fluid pressures and decreased traction. These trends are presumably due to reduced fluid drainage between the shoe-floor interface when the shoe becomes worn.

Conclusions—Traction performance changes with natural wear. The distance walked in the shoe and the size of the worn region may be valuable indicators for assessing loss of traction performance.

Practical Applications—Current shoe replacement recommendations for slip-resistant shoes are based upon age and tread depth. This study suggests that tools measuring the size of the worn

Corresponding author: Kurt E. Beschorner beschorn@pitt.edu.

Publisher's Disclaimer: This is a PDF file of an unedited manuscript that has been accepted for publication. As a service to our customers we are providing this early version of the manuscript. The manuscript will undergo copyediting, typesetting, and review of the resulting proof before it is published in its final form. Please note that during the production process errors may be discovered which could affect the content, and all legal disclaimers that apply to the journal pertain.

region and/or distance traveled in the shoes are appropriate alternatives for tracking traction performance loss due to shoe wear.

Keywords

Slips, trips, & falls; biomechanics; shoe wear; available coefficient of friction; footwear

1. Problem

Slips, trips, and falls are a major concern in the workplace. In 2017, they accounted for 26% of nonfatal occupation injuries in the United States (U.S. Department of Labor - Bureau of Labor Statistics, 2019). According to a 2017 report, over \$18 billion was devoted to workers' compensation from falls (Liberty Mutual Research Institute for Safety, 2017). Over 40% of all fall-related injuries have been shown to result from slipping (Courtney, Sorock, Manning, Collins, & Holbein-Jenny, 2001).

A slipping event occurs when there is insufficient traction between the shoe and the floor, often in the presence of a liquid contaminant (Burnfield & Powers, 2006; Hanson, Redfern, & Mazumdar, 1999). The measure typically describing this traction between two surfaces that resists slipping is the available coefficient of friction (ACOF). The ACOF of footwear can be measured using a variety of mechanical slip-testing devices that slide a shoe across a contaminated surface approximating a slipping event (Aschan, Hirvonen, Mannelin, & Rajamäki, 2005; Beschorner, Redfern, Porter, & Debski, 2007; Chang et al., 2001; Grönqvist, 1995; Hemler, Charbonneau, et al., 2019; Singh & Beschorner, 2014).

Footwear is a modifiable factor for reducing slips in the workplace. Shoes marketed as slip-resistant (SR) have been shown to have greater ACOF (Beschorner, Jones, & Iraqi, 2017) and a reduced rate of slipping compared to non-SR shoes (Verma et al., 2011). The outsoles of SR shoes tend to have patterns of small tread that are separated by channels. The channels provide paths for fluid drainage in the presence of a liquid contaminant (Hemler, Charbonneau, et al., 2019; Strandberg, 1985; Tisserand, 1985). The absence of tread channels can cause the fluid between a shoe and flooring to become pressurized. High fluid pressures indicate that the shoe-floor contaminant system is operating in the mixed lubrication regime, resulting in a lower ACOF (Beschorner et al., 2017; Beschorner, Lovell, Higgs III, & Redfern, 2009; Moore, Menezes, Lovell, & Beschorner, 2012; Singh & Beschorner, 2014). This phenomenon has been verified during human participant testing; specifically, wearing SR shoes was associated with lower under-shoe fluid pressures and lower slip severity compared to non-SR shoes (Sundaram et al., 2020; Hemler, Sundaram, & Beschorner, 2019). While footwear is clearly an important factor influencing slip risk, an incomplete understanding exists for how traction performance changes as the shoes become worn.

There is currently a paucity of research quantifying changes in the traction performance of shoes as the outsole becomes worn and tread patterns are reduced. Previous research has shown that newer shoes were associated with a reduction in workplace slip risk compared to older shoes (Verma et al., 2014). Furthermore, switching to a new pair of shoes in the workplace reduced slipping rate by 55% (Verma et al., 2014). However, this previous study

assessed wear using just two time categories (<6 months and >6 months). Current shoe manufacturers provide shoe tread depth gauges for determining significant wear (ShoesForCrews, 2019). However, there could be confusion regarding the location for application of tread depth gauges since tread wears unevenly (Hemler, Charbonneau, et al., 2019). A longitudinal shoe wear study that tracked shoes based on reported months of wear found slight increases in ACOF with initial wear followed by decreases in ACOF with subsequent wear (Grönqvist, 1995). Traction performance of shoes progressively worn using an accelerated wear protocol of abrasive mechanical sliding has shown increased fluid pressures and decreased ACOF as shoes become worn (Hemler, Charbonneau, et al., 2019). High fluid pressures were identified as mechanisms contributing to reduced ACOF (Sundaram et al., 2020 and Hemler et al., 2020). However, the effects of natural wear on ACOF is not well understood.

Recent research has determined that the size of the worn region is associated with under-shoe hydrodynamics, which may explain the loss of traction as shoes wear. Analysis of shoes worn down using abrasive mechanical sliding showed that the under-shoe fluid pressures increased as the size of the worn region grew (Hemler, Charbonneau, et al., 2019). This concept is consistent with hydrodynamics models (e.g., rectangular tapered wedge bearing) that predict an increase in film thickness of the fluid separating two surfaces (Fuller, 1956) and increased fluid pressures with a larger worn region. Preliminary research has shown that the size of the worn region may be a useful factor in predicting this film thickness between a shoe and floor, relevant to a slipping event (Hemler & Beschoner, 2019). This study aims to further this research by analyzing the effects of the size of the worn region on traction and fluid drainage for naturally worn shoes.

The purpose of this study was to quantify the effects of usage (distance walked) and wear (size of the worn region) on changes in traction performance (ACOF and under-shoe fluid drainage). A preliminary data set from a longitudinal study is presented.

2. Method

In the longitudinal study, each participant received slip-resistant shoes that were worn in the workplace every other month to allow for traction performance and size of the worn region data collection on the months when the shoes were not worn. The distance the shoes were worn was tracked using a pedometer. At baseline and after each month of wear, ACOF and under-shoe fluid drainage measurements were collected. To record the geometry of the tread, negative molds of the heel tread were created. This paper presents initial findings for data collected so far from this study.

2.1. Subjects & Shoes

Seven participants (1 female participant – age: 26 years; height: 175 cm; mass: 76.8 kg; shoe size: 7.5 US Men's Sizing – and 6 males – mean age: 45.8 ± 12.3 years; mean height: 185.3 ± 10.0 cm; mean mass: $100. \pm 8.3$ kg; mean shoe size: $12. \pm 1.7$ US Men's Sizing) wearing one of the shoe brands from a larger study were included. The other requirement for inclusion was a cumulative walking distance of more than 200 km. The included participants were employed in diverse settings including transportation, utilities, education, health

services, and the hospitality industry sectors. Inclusion criteria included: regularly wearing treaded shoes in the workplace; working on their feet for at least four hours in a typical day; having a BMI less than 35; and having no history of musculoskeletal injury in the previous 2 years. The study was approved by the University of Pittsburgh Institutional Review Board and the participants provided informed consent prior to participation in the study.

Participants were provided with either boots (safeTstep®, Dawson 160004) or shoes (safeTstep®, Blast Bouffee 159961) depending on their occupational requirements. Both the boots and shoes had the same tread design (Figure 1). The shoe outsole material was rubber with a Shore A Hardness of 65 for the shoe and 74 for the boot. Each shoe was outfitted with a pedometer (MilestonePod, Milestone Sports, Columbia, MD), (Hunter, Miller, & Suydam, 2017) to track the distance traveled in each shoe. Shoes were retired from the study when the under-shoe fluid force for either the left or right shoe was greater than 50 N (see Section 2.4), or when the outsole or upper (i.e., part of the shoe or boot above the sole) became too worn at the discretion of the participant.

2.2. Mechanical Testing of Shoes

A robotic slip tester (Figure 2) was used to assess the traction performance of the shoes (see Hemler, Charbonneau, et al., 2019 for details). The device consisted of a force plate measuring shear and normal forces (BP400600–1K-Q2046, AMTI, Watertown, MA, 02472), an adjustable platform instrumented with fluid pressure sensors (Gems® 3100R10PG08F002) aligned in the X-direction, and three electromagnetic motors. One motor controlled the vertical displacement (Z-direction), and the two horizontal motors controlled the horizontal displacement (Y-direction) and the foot angle (YZ plane). Four fluid pressure sensors were aligned in the X-direction, embedded beneath the floor, spaced 25 mm apart and had an inlet diameter of 3.2 mm. The device is similar to the Portable Slip Simulator device (Aschan et al., 2005; Iraqi, Cham, Redfern, & Beschoner, 2018; Jones, Iraqi, & Beschoner, 2018). Additionally this device has the ability to independently control the foot angle and has been used in previous research for traction performance testing (Hemler, Charbonneau, et al., 2019).

Using the robotic slip tester, the right and left shoes of each pair were tested using a contaminated surface at baseline and after each month of wear. A vinyl composite tile flooring (Armstrong, 51804; with surface roughness characteristics: $R_a = 2.19 \pm 0.29 \mu\text{m}$, $R_z = 16.13 \pm 2.74 \mu\text{m}$, $R_q = 3.13 \pm 0.42 \mu\text{m}$; where R_a is the average asperity deviation from the mean line, R_z is the maximum asperity peak to valley distance, and R_q is the root mean square height of the profile) and a diluted glycerol contaminant solution (90% glycerol, 10% water by volume; 219 cP) were used. A sufficient amount of fluid was applied to the flooring to fully cover the floor asperities across the region that the shoe contacted. The contaminant was spread to cover the entire slipping area prior to each trial. To approximate the same conditions as a slipping incident, each shoe was slid at an angle of $17 \pm 1^\circ$ (Albert, Moyer, & Beschoner, 2017; Iraqi, Cham, Redfern, & Beschoner, 2018), speed of 0.3 m/s (Albert et al., 2017; ASTM, 2011; Iraqi, Cham, Redfern, & Beschoner, 2018), and average normal force of $250 \text{ N} \pm 10 \text{ N}$ (Iraqi & Beschoner, 2017; Iraqi, Cham, Redfern, Vidic, &

Beschorner, 2018). The platform was moved 5 mm in the positive X-direction between each trial for a total of 5 trials and 20 fluid pressure scans.

2.3. Worn region measurement

A mold of the heel tread was made at baseline and after each month of wear. The left and right heels were placed in a rectangular containment (92 mm × 76 mm × 28 mm) of silicone rubber compound (Smooth-On Inc.; Macungie, PA; Oomoo® 25) at an angle of 17° (Figure 3). The largest region of continuous wear was identified in each mold and the length along the long axis of the shoe and the width along the short axis of the shoe were measured. For baseline values and when no worn region had yet formed, the length and width of one tread block was recorded. The product of these two measurements comprised the size of the worn region on each shoe.

2.4. Data analysis

The ACOF was determined as the peak of the ratio of the resultant shear forces to the normal force, averaged across a 200 ms time period. This time period started when the normal force first reached 250 N. Fluid pressures that exceeded 10 kPa were included in the analysis. A numerical integration technique was used to determine the load supported by the fluid (hereafter, referred to as the fluid force) for each shoe (Beschorner, Albert, Chambers, & Redfern, 2014; Hemler, Charbonneau, et al., 2019). If either the right or left shoe reached a fluid force greater than 50 N, the pair of shoes was retired from the study as it was deemed unsafe for continued use (Hemler, Charbonneau, et al., 2019).

The aims of this study were to quantify traction performance in response to increased usage and growth of the size of the worn region. Thus, the ACOF and fluid force were the dependent variables. Predictor variables included the distance walked and size of the worn region. The analyses controlled for shoe side (left vs. right).

Repeated-measures ANOVA methods were used to analyze the effects of the predictor variables (size of worn region, distance walked) on the dependent variables (ACOF, fluid force). Specifically, two models were used to determine the response of ACOF and fluid force to the distance walked in the shoes (continuous). Two additional models were used to determine the response of ACOF and fluid force to the size of the worn region (continuous). Separate analyses were used for distance walked and the size of the worn region as predictor variables since these variables are correlated (Supplementary Materials). Participant was a random variable in these models. To normalize the residuals, a square transformation was applied to the ACOF data and a cube root transformation was applied to fluid force data prior to statistical analyses. To correct for a positive skew, a square root transformation was applied to the distance walked.

3. Results

A total of 35 subject-months of data are reported ranging from 3 to 10 months per participant. The total distance walked ranged from 220 to 1255 km with an average ± standard deviation total distance of 23±262 km and a monthly average of 7±82 km. One pair of shoes was retired from the study due to the left shoe exceeding the 50 N fluid force safety

threshold. Four pairs of shoes were retired due to significant wear to the footwear upper. Two participants are still enrolled in the study (S6 & S7). For all shoes, the worn region began in a single region (13 cases on the lateral side and 1 case on the medial side) and a single wear patch grew with subsequent use.

The ACOF ranged from 0.081 to 0.212 (Figure 4) throughout the study and ACOF ranged from 0.134 to 0.184 (shoes). Of these shoes, the ACOF fell below the baseline ACOF after 128 ± 64 km of wear. After 210 km of wear, ACOF decreased from the baseline level for all shoes. The average ACOF decrease was 0.053 ± 0.032 ($28.1 \pm 13.6\%$) from baseline to present data collection. Across participants, the average (standard deviation) ACOF at baseline, from 0–200 km, and at each participant's last datum were 0.18 (0.023), 0.17 (0.030), and 0.13 (0.022), respectively.

An increase in the distance walked was associated with increased fluid force ($F_{1,86}=44.2$, $p < .001$). The fluid force ranged from <0.1 to 63.8 N (Figure 5). Using the regression equation (fluid force [N] = $(1.16 + 0.05\sqrt{\text{Distance Walked [km]}})^3$), walking distances of 200 km and 1000 km were associated with an increase in fluid force of 6 N and 19 N, respectively.

The size of the worn region ranged from 12 to 2432 mm² and increased with respect to the distance walked (additional details available in Supplemental Materials) (Figure 6). ACOF decreased as the size of the worn region increased ($F_{1,85}=36.0$, $p < .001$). When the size of the worn region grew to 1000 mm² and 2000 mm², the ACOF was predicted to decrease from baseline by 0.03 and 0.08, respectively ($\text{ACOF} = \sqrt{0.03 - 0.000011 * \text{SWR [mm}^2\text{]}}$). The increase in fluid force was associated with increases in the size of the worn region ($F_{1,76}=59.2$, $p < .001$). Using the regression equation, fluid force [N] = $(1.3 + 0.00086 * \text{SWR [mm}^2\text{]})^3$, the fluid force was predicted as 11 N after the size of the worn region grew to 1000 mm² and as 29 N after the size of the worn region reached 2000 mm².

4. Discussion

In this study, ACOF decreased and the fluid force generally increased as SR shoes became more worn. The increase in fluid pressure partially explains the decreased traction. There was an initial increase in ACOF from baseline for 9 of the 14 shoes, though the ACOF then decreased from baseline for all of the shoes after at most, 210 km of usage. The fluid force increase was associated with the increasing size of the worn region, presumably due to reduced fluid drainage.

The effects of usage and wear on ACOF and fluid force from this analysis are consistent with previous research. For progressively worn shoes using natural and simulated wear respectively, Grönqvist (1995) and Hemler et al. (2019) reported an initial increase in ACOF followed by a decrease across the life of the shoes. In this study, similar trends are seen for the majority of the naturally worn shoes with an initial increase in ACOF for distances less than 210 km and subsequent decrease in ACOF. The increase in fluid force with increased wear is also consistent with previous studies (Hemler, Charbonneau, et al., 2019). The relationship between fluid force and size of the worn region is consistent with previous research that utilized an accelerated wear protocol to generate shoe wear (Hemler,

Charbonneau, et al., 2019). Fluid force increased as the size of the worn region increased similar to Hemler, Charbonneau, et al. (2019), and consistent with hydrodynamic theory (Hamrock, Schmid, & Jacobson, 2004). Therefore, this study adds to a growing body of evidence that traction performance degrades over usage and that this degradation can be assessed based on the size of the worn region.

The variation of ACOF observed in this study was within a critical range for determining slip likelihood. Human slipping studies have shown that the probability of a slip on level ground changes dramatically within the range of 0.12–0.21 (Burnfield & Powers, 2006; Hanson et al., 1999; Iraqi, Cham, Redfern, & Beschorner, 2018). Both the baseline ACOF values and the changes in ACOF due to wear vary within this range. This variability is not believed to be due to the device since repeatability is less than 0.01 for the portable slip tester (Beschorner, Iraqi, Redfern, Moyer, & Cham, 2020), which is functionally similar to the slip testing device used in this study. The variation in ACOF at baseline for the shoes may be due to different heel tread block placements that arise from variations in shoe size-dependent molds (Fig 4A). For example, on the heel, the general tread pattern is the same for all shoes. However, on the edges, some individual tread blocks are cut differently to fit the heel of the appropriate shoe size. These variations in tread on the edges may affect the ACOF.

This preliminary study has certain limitations. A single shoe tread pattern was used in order to limit variability across the participants. However, this limited the generalizability of the results to other types of shoes. The shoes were tested on the slip-testing device with a 0° medio-lateral tilt. Wear generally appeared first on the lateral side of the shoe outsoles, which may indicate that participants walked with a slight medio-lateral inversion. The slip testing device was unable to accommodate individual inversion angles, which may have led to the tread contact region being incongruent between traction performance testing and actual walking.

5. Summary

The results found an association between the size of the worn tread region and traction performance loss for naturally worn, slip-resistant shoes. Consistent with accelerated wear experiments, an initial increase in friction was observed at low distances of usage followed by a steady decrease in friction with increasing distance. Fluid force measurements suggest that this steady decrease in traction is caused by an increase in hydrodynamic effects. The increase in hydrodynamic effects coincide with an increase in the size of the worn region, consistent with hydrodynamic theory. This study supports that usage and wear measures presented in this study are beneficial tools in mapping traction performance for slip-resistant shoes.

6. Practical Applications

The distance for which shoes have been worn and the size of the worn region may be useful tools for monitoring traction performance changes. Specifically, these metrics correlate with ACOF and fluid force and are realistic for determining shoe replacement thresholds for

natural wear. For example, observing the size of the worn region is achievable via self-monitoring and the distance walked is practical to monitor given increased use of wearable sensors for worker safety monitoring. Thus, these metrics may provide an opportunity for employers and employees to monitor shoe wear condition to inform replacement.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

Acknowledgements

This study was funded by grants from the National Institute for Occupational Safety & Health (NIOSH R01 OH 010940), the National Science Foundation (NSF GRFP 1747452), and the National Institute of Arthritis and Musculoskeletal and Skin Diseases (R43AR064111). The authors would like to acknowledge the lab manager of the Human Movement and Balance Laboratory, Jenna Trout, and the undergraduates on the project who contributed to data collection through testing the shoes and coordinating with the participants: Catherine (Grace) Hobayan, Michael Limbacher, Ellen Martin, Bridget Moyer, Claire Tushak, & Paul Walter.

Biography

Sarah Hemler, B.S. is a PhD student and NSF Graduate Research Fellow in the Bioengineering Department at the University of Pittsburgh under the advisement of Dr. Kurt Beschorner. She obtained her bachelor's degree in Mechanical Engineering from the University of Maryland, Baltimore County. Her research has covered strength interventions for persons with disabilities and mobile technologies for detecting traumatic brain injury, with her most recent work studying progressive shoe wear and the impacts of shoe tread design on slipping.

Erika Pliner, Ph.D. is a post-doctoral researcher at the University of Pittsburgh. She completed her bachelor's degree in Mechanical Engineering, her master's degree in Engineering at the University of Wisconsin-Milwaukee, and her Ph.D. at the University of Pittsburgh. Erika is an NSF Graduate Research Fellow and Whitaker Foundation Fellow. Her current research focuses on identifying mechanisms of ladder falls.

Mark S. Redfern, Ph.D. is the William Kepler Whiteford professor of Bioengineering at the University of Pittsburgh. He received his doctoral degree in Bioengineering in 1988 from the University of Michigan.

Joel M. Haight, Ph.D. is an Associate Professor in the Department of Industrial Engineering at the University of Pittsburgh and Director of the Safety Engineering Program. He received his doctoral degree in Industrial and Systems Engineering in 1999 from Auburn University.

Kurt Beschorner, Ph.D. is an Associate Professor of Bioengineering at the University of Pittsburgh. His research mission is to apply core competencies in tribology, biomechanics, and ergonomics to prevent falling accidents. He received his B.S. in Mechanical Engineering from the University of Illinois Urbana-Champaign and his Ph.D. in Bioengineering from the University of Pittsburgh.

7. References

- Albert DL, Moyer BE, & Beschoner KE (2017). Three-Dimensional Shoe Kinematics During Unexpected Slips: Implications for Shoe–Floor Friction Testing. *IIEE Transactions on Occupational Ergonomics and Human Factors*, 5(1), 1–11.
- Aschan C, Hirvonen M, Mannelin T, & Rajamäki E (2005). Development and validation of a novel portable slip simulator. *Applied ergonomics*, 36(5), 585–593. [PubMed: 15970203]
- ASTM, American Society for Testing and Materials. (2011). ASTM F2913–11: Standard Test method for Measuring the Coefficient of Friction for Evaluation of Slip performance of Footwear and Test Surfaces/Flooring Using a Whole Shoe Tester. In. West Conshohocken, PA: ASTM International.
- Beschoner KE, Albert DL, Chambers AJ, & Redfern MS (2014). Fluid pressures at the shoe– floor–contaminant interface during slips: Effects of tread & implications on slip severity. *Journal of Biomechanics*, 47(2), 458–463. [PubMed: 24267270]
- Beschoner KE, Iraqi A, Redfern MS, Moyer BE, & Cham R (2020). Influence of averaging time-interval on shoe-floor-contaminant available coefficient of friction measurements. *Applied Ergonomics*, 82, 102959. [PubMed: 31568960]
- Beschoner KE, Jones TG, & Iraqi A (2017). The Combined Benefits of Slip-Resistant Shoes and High Traction Flooring on Coefficient of Friction Exceeds Their Individual Contributions. Paper presented at the Proceedings of the Human Factors and Ergonomics Society Annual Meeting.
- Beschoner KE, Lovell M, Higgs III CF, & Redfern MS (2009). Modeling mixed-lubrication of a shoe-floor interface applied to a pin-on-disk apparatus. *Tribology Transactions*, 52(4), 560–568.
- Beschoner KE, Redfern MS, Porter WL, & Debski RE (2007). Effects of slip testing parameters on measured coefficient of friction. *Applied ergonomics*, 38(6), 773–780. [PubMed: 17196925]
- Burnfield JM, & Powers CM (2006). Prediction of slips: an evaluation of utilized coefficient of friction and available slip resistance. *Ergonomics*, 49(10), 982–995. [PubMed: 16803728]
- Chang W-R, Grönqvist R, Leclercq S, Brungraber RJ, Mattke U, Strandberg L, ... Courtney TK (2001). The role of friction in the measurement of slipperiness, Part 2: Survey of friction measurement devices. *Ergonomics*, 44 (13), 1233–1261. [PubMed: 11794766]
- Courtney TK, Sorock GS, Manning DP, Collins JW, & Holbein-Jenny MA (2001). Occupational slip, trip, and fall-related injuries—can the contribution of slipperiness be isolated? *Ergonomics*, 44(13), 1118–1137. [PubMed: 11794761]
- Fuller D (1956). *Theory and Practice of Lubrication for Engineers*. New York: John Wiley & Sons, Inc.
- Grönqvist R (1995). Mechanisms of friction and assessment of slip resistance of new and used footwear soles on contaminated floors. *Ergonomics*, 38(2), 224–241. [PubMed: 28084937]
- Hamrock BJ, Schmid SR, & Jacobson BO (2004). *Fundamentals of fluid film lubrication*: CRC Press.
- Hanson JP, Redfern MS, & Mazumdar M (1999). Predicting slips and falls considering required and available friction. *Ergonomics*, 42(12), 1619–1633. [PubMed: 10643404]
- Hemler SL, & Beschoner KE (2019). Predicting Slip Risk Based on Footwear Paper presented at the Society of Tribologists and Lubrication Engineers, Nashville, TN.
- Hemler SL, Charbonneau DN, Iraqi A, Redfern MS, Haight JM, Moyer BE, & Beschoner KE (2019). Changes in under-shoe traction and fluid drainage for progressively worn shoe tread. *Applied ergonomics*, 80, 35–42. [PubMed: 31280808]
- Hemler SL, Sundaram VH, & Beschoner KE (2019). Influence of slip-resistant shoe classification and shoe age on under-shoe hydrodynamics during human slips. Paper presented at the International Society of Biomechanics & American Society of Biomechanics, Calgary, Alberta, Canada.
- Hemler SL, Charbonneau DN, & Beschoner KE (2020). Predicting hydrodynamic conditions under worn shoes using the tapered-wedge solution of Reynolds equation. *Tribology International*, 145, 106161. [PubMed: 32863531]
- Hunter JG, Miller RH, & Suydam S (2017). Accuracy of a shoe-worn device to measure running mechanics.

- Iraqi A, & Beschorner KE (2017). Vertical Ground Reaction Forces During Unexpected Human Slips. Paper presented at the Proceedings of the Human Factors and Ergonomics Society Annual Meeting.
- Iraqi A, Cham R, Redfern MS, & Beschorner KE (2018). Coefficient of friction testing parameters influence the prediction of human slips. *Applied ergonomics*, 70, 118–126. [PubMed: 29866300]
- Iraqi A, Cham R, Redfern MS, Vidic NS, & Beschorner KE (2018). Kinematics and kinetics of the shoe during human slips. *Journal of Biomechanics*, 74, 57–63. [PubMed: 29759653]
- Jones TG, Iraqi A, & Beschorner KE (2018). Performance testing of work shoes labeled as slip resistant. *Applied ergonomics*, 68, 304–312. [PubMed: 29409649]
- Liberty Mutual Research Institute for Safety. (2017). 2017 Liberty Mutual Workplace Safety Index. Retrieved from <https://www.libertymutualgroup.com/about-liberty-mutual-site/news-site/Pages/2017-Liberty-Mutual-Workplace-Safety-Index.aspx>
- Moore CT, Menezes PL, Lovell MR, & Beschorner KE (2012). Analysis of shoe friction during sliding against floor material: role of fluid contaminant. *Journal of Tribology*, 134(4), 041104.
- ShoesForCrews. (2019). Shoe Care and Cleaning Tips. Accessed 18 January 2019 Retrieved from https://www.shoesforcrews.com/sfc3/index.cfm?changeWebsite=US_en&route=inserts.QA/cleaning_caring
- Singh G, & Beschorner KE (2014). A Method for Measuring Fluid Pressures in the Shoe–Floor–Fluid Interface: Application to Shoe Tread Evaluation. *IIE Transactions on Occupational Ergonomics and Human Factors*, 2(2), 53–59. [PubMed: 31106007]
- Strandberg L (1985). The effect of conditions underfoot on falling and overexertion accidents. *Ergonomics*, 28(1), 131–147. [PubMed: 3996350]
- Sundaram VH, Hemler SL, Chanda A, Haight JM, Redfern MS, & Beschorner KE (2020). Worn region size of shoe outsole impacts human slips: Testing a mechanistic model. *Journal of Biomechanics*, 105, 109797. [PubMed: 32423543]
- Tisserand M (1985). Progress in the prevention of falls caused by slipping. *Ergonomics*, 28(7), 1027–1042. [PubMed: 4043027]
- U.S. Department of Labor - Bureau of Labor Statistics. (2019). Nonfatal Occupational Injuries and Illnesses Requiring Days Away From Work, 2017. Retrieved from Washington, D.C.:
- Verma SK, Chang WR, Courtney TK, Lombardi DA, Huang Y-H, Brennan MJ, ... Perry MJ (2011). A prospective study of floor surface, shoes, floor cleaning and slipping in US limited-service restaurant workers. *Occupational and environmental medicine*, 68(4), 279–285. [PubMed: 20935283]
- Verma SK, Zhao Z, Courtney TK, Chang W-R, Lombardi DA, Huang Y-H, ... Perry MJ (2014). Duration of slip-resistant shoe usage and the rate of slipping in limited-service restaurants: results from a prospective and crossover study. *Ergonomics*, 57(12), 1919–1926. [PubMed: 25205136]

Highlights

- A knowledge gap exists regarding changes in shoe traction as tread becomes worn.
- The traction performance from seven participants wearing slip-resistant shoes were tracked.
- Coefficient of friction (ACOF) and under-shoe fluid drainage were measured monthly.
- Wear progression led to a decrease in ACOF and reduced under-shoe fluid drainage.
- Replacing shoes based on distance walked or the wear condition may prevent slips.



Figure 1.
Shoe tread pattern at the heel for all shoes in this study.

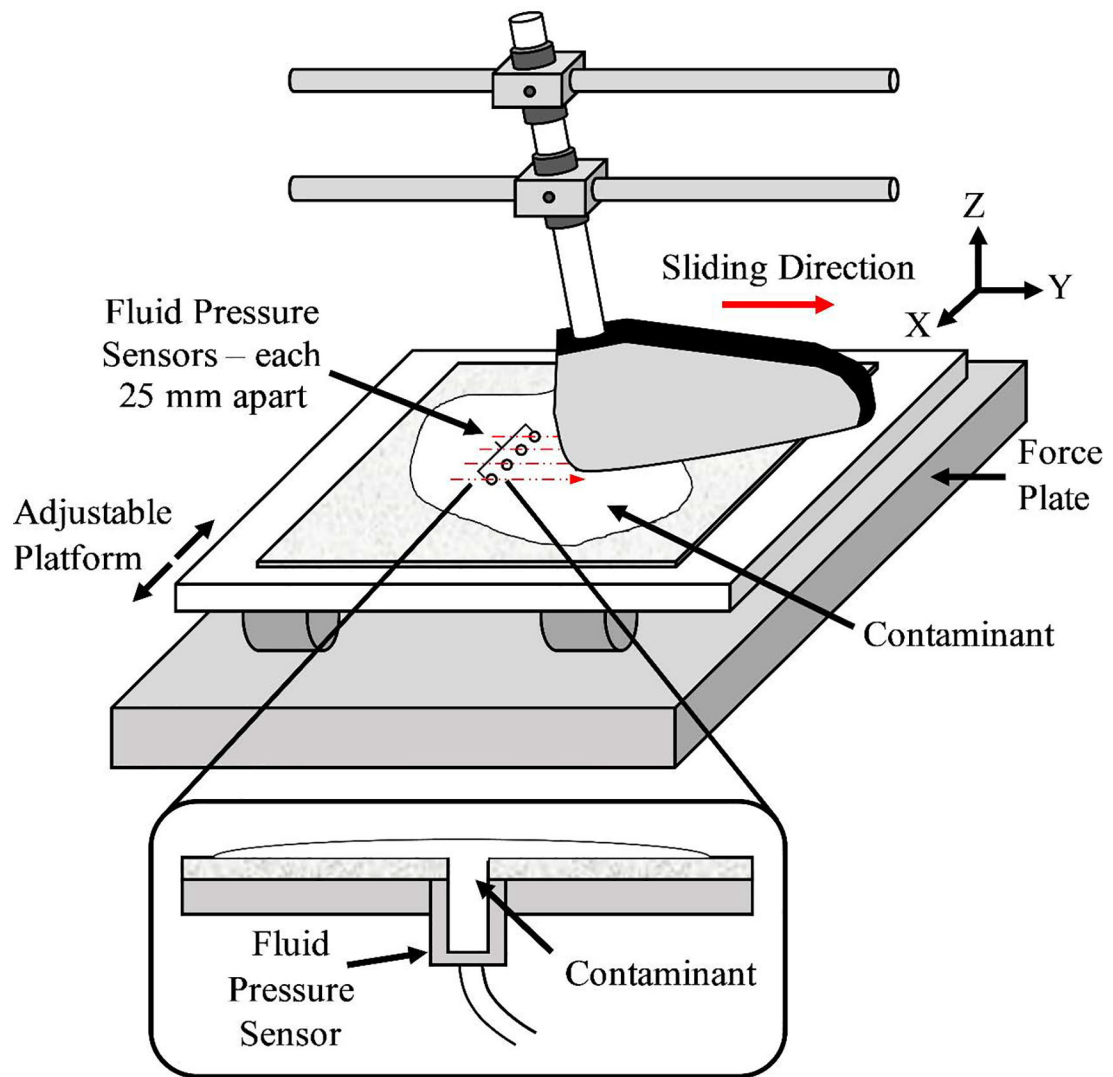


Figure 2.
The robotic slip tester was used to slide the shoe across the contaminated surface along multiple parallel paths (adapted from Hemler, Charbonneau, et al., 2019).

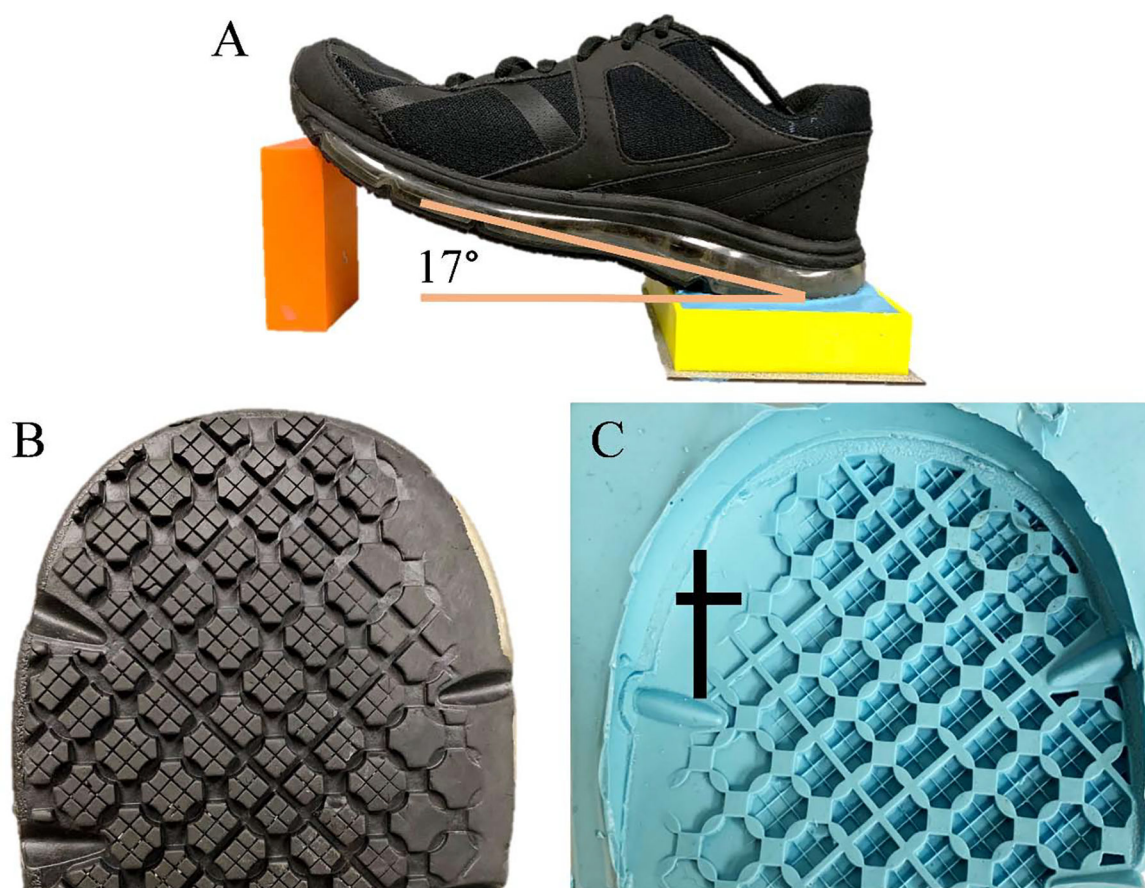


Figure 3.

A) Molds of shoe heels were created at a 17° angle to capture the B) shoe tread geometry. C) The mold was used to measure the length and the width of the largest continuous area without tread at baseline and after each month of wear.

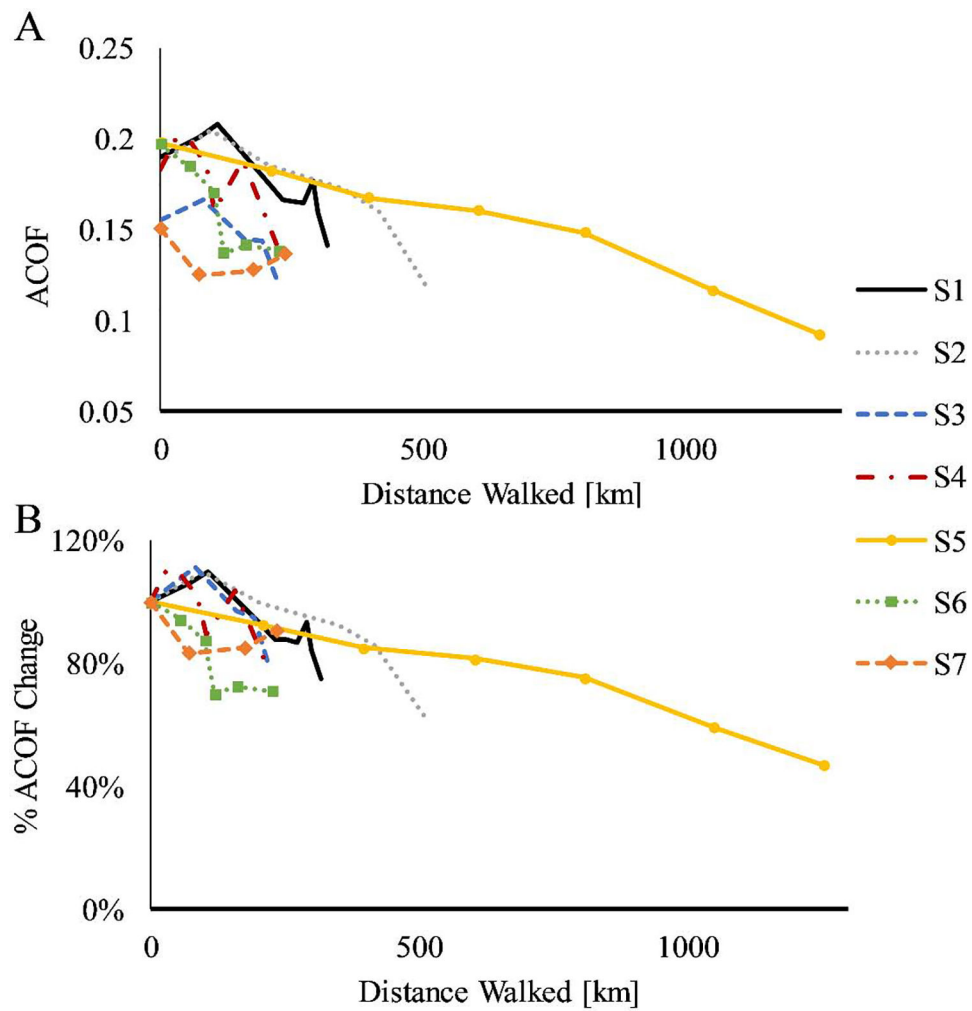


Figure 4.

A) ACOF plotted against the distance walked for each participant. B) ACOF across the distance walked in the shoes as a percentage of the baseline ACOF. ACOF and percent of baseline ACOF are averaged across left and right shoe sides.

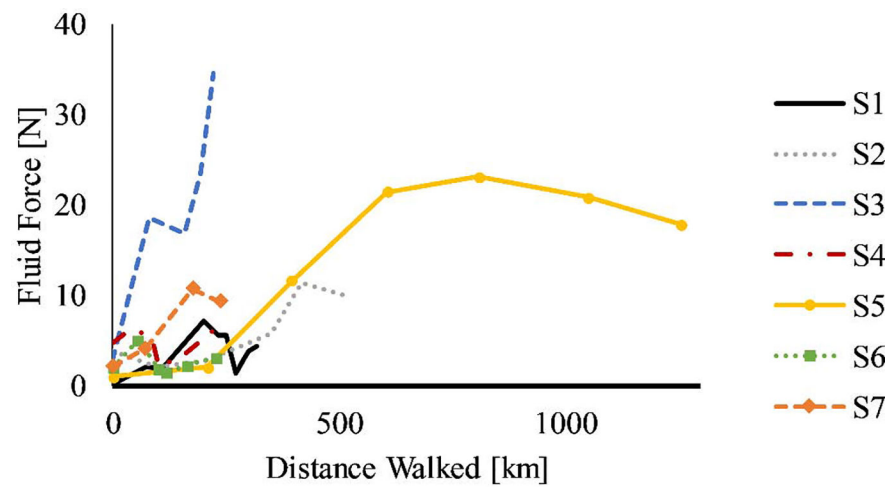


Figure 5.

Fluid force values are plotted against the distance walked which was averaged across the left and right shoes per subject.

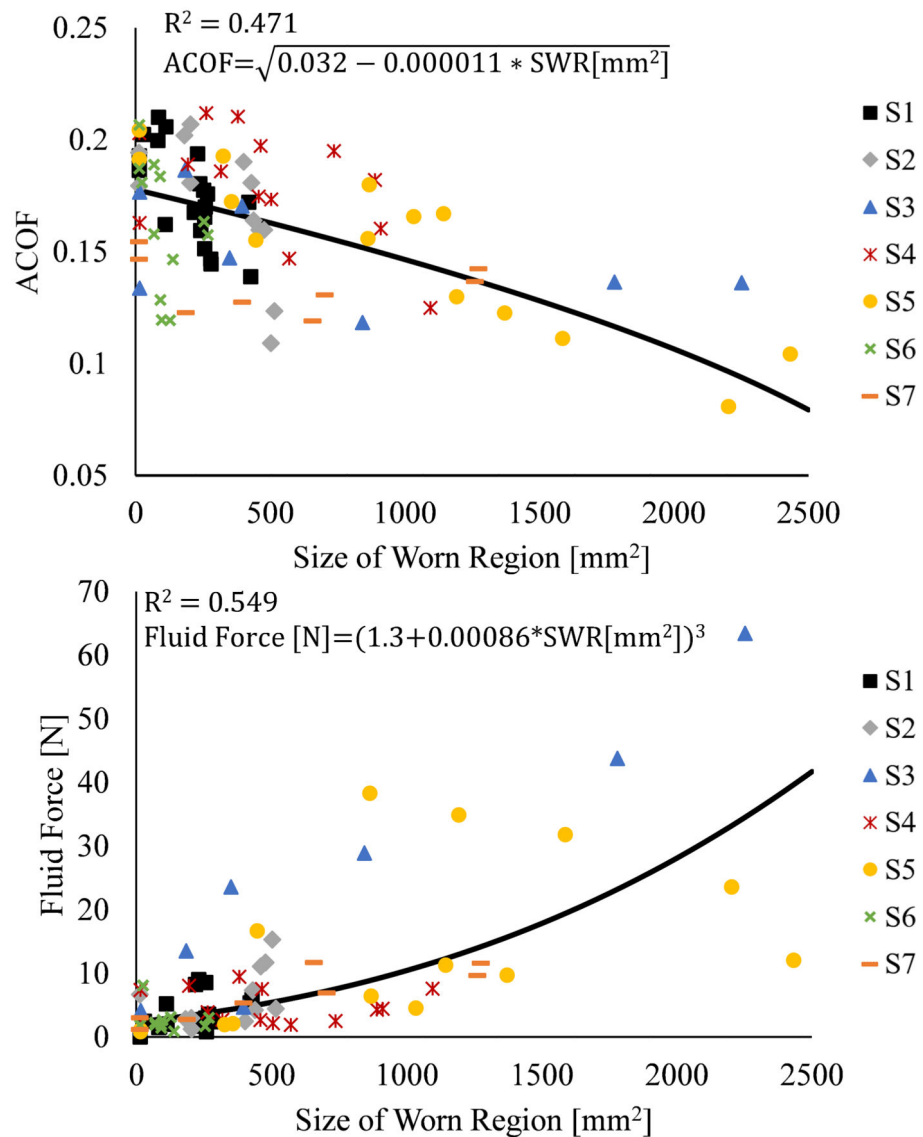


Figure 6.

A) ACOF plotted against the size of the worn region. Different markers are used for each participant (legend). B) Fluid force plotted against the size of the worn region for all participants. Left and right shoe averages are shown for each participant. The regression functions for each model are shown with the solid black line (SWR = size of worn region [mm²]). The regression equations and the R^2 values are shown in the top left of each plot.